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NUMERICAL MODELING OF FISH EGGS TRANSPORT IN THE BACKWATER OF THE JIRAU HYDROPOWER DAM, MADEIRA RIVER-BRAZIL

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Abstract. *The Madeira River has over 950 species of fish, some of which are rare among the world ichthyological collections. Many of these are migratory species impact the reproductive stocks that live in the Amazon River. Numerical simulations to predict fish eggs transport are scarce in hydropower plants studies in the Amazonian rivers. This work deals with the investigation of the drift processes of fish eggs in the backwater of the Jirau Dam at the Madeira River in the Brazilian Amazonian region. The model describes the fish eggs as passive particles and adopts a second order Lagrangian scheme, which is coupled with the hydrodynamic model implemented in SisBaHiA (Base System for Environmental Hydrodynamic). Numerical results are analyzed in terms of the hydrological and meteorological conditions controlling the transport of eggs and the extension of their excursion, from upstream up to the dam and indicate that fish eggs migration through the project area will continue unhindered.*

Keywords: *Fish eggs drift, environmental modeling, Jirau Dam*

1. INTRODUCTION

The Brazilian Amazon basin has a great hydroelectric potential where new dams are under construction or planned (Soito and Freitas, 2011), such as Jirau and Santo Antonio hydropower dams both in Madeira River. Scientific studies have identified some potential effects of these developments, for instance, blockage to the upstream migration of fishes species. It is worth to note that the Amazon rivers have the greatest diversity of freshwater fishes in the world, some of which are still unknown to science (Godinho *et al.*, 2013). The Madeira River, for example, is home to more than 950 species of freshwater fishes, which are rare among the world's ichthyological collections, and nearly 40 species are still waiting for scientific descriptions (see, e.g., www.labictio.unir.br). The migratory of fish species and the drift of fish eggs and larvae are important environmental issue facing hydropower dams construction. The migration of fish species at dams has been severely studied, but how changes in the hydrodynamics of the river upstream and downstream of dams constructions might be affected the drift of fish eggs and larvae is difficult to establish. The prediction this effect is essential to environmental assessments.

The Jirau hydropower dam project is under construction in the Municipality of Porto Velho, in the State of Rondônia, northern Brazil, see Fig.1. It will have an installed capacity of 3750 MW (using 50 units of 75 MW bulb turbines). One powerhouse, to be equipped with 28 units, will be located on the right bank and a second powerhouse, on the left bank, will have 22 units. The centrally located spillway will be equipped with 18 radial gates, 21.82 m high and 20 m wide (for passing a discharge of 82 600 m^3 s^{-1}, which corresponding to a 10 000 year flood). To mitigate impacts to the natural upstream water level of the Madeira river might reach, the hydropower will operate with a variable upper reservoir level; the minimum water level will be 82.5 m, the maximum normal water level will be 90 m, and the maximum highest water level will be 92 m (Alam *et al.*, 2010).

Due to of the possible environmental alterations caused by the Jirau dam's construction, on the Madeira River, the purpose of this study is to verify the behavior of the drift of fish eggs and larvae and the extension of their excursion in the Jirau reservoir towards the understanding of the mechanisms controlling the drift of fish eggs in Jirau reservoir. This is the first attempt to couple physical forcing to study the mechanisms that influence in the drift of fish eggs in the river. Results of this study will significantly contribute to understand recruitment dynamics and enhance resource management in hydropower dam in rivers in the Northern Brazil that are complex and still little understood. Further, to achieve this goal, we consider a coupled hydrodynamics and Lagrangian model.

In Section 2, we present the hydrodynamic and particle tracking models. Section 3 presents the results and discussion. Finally, in Section 4 we present conclusions.

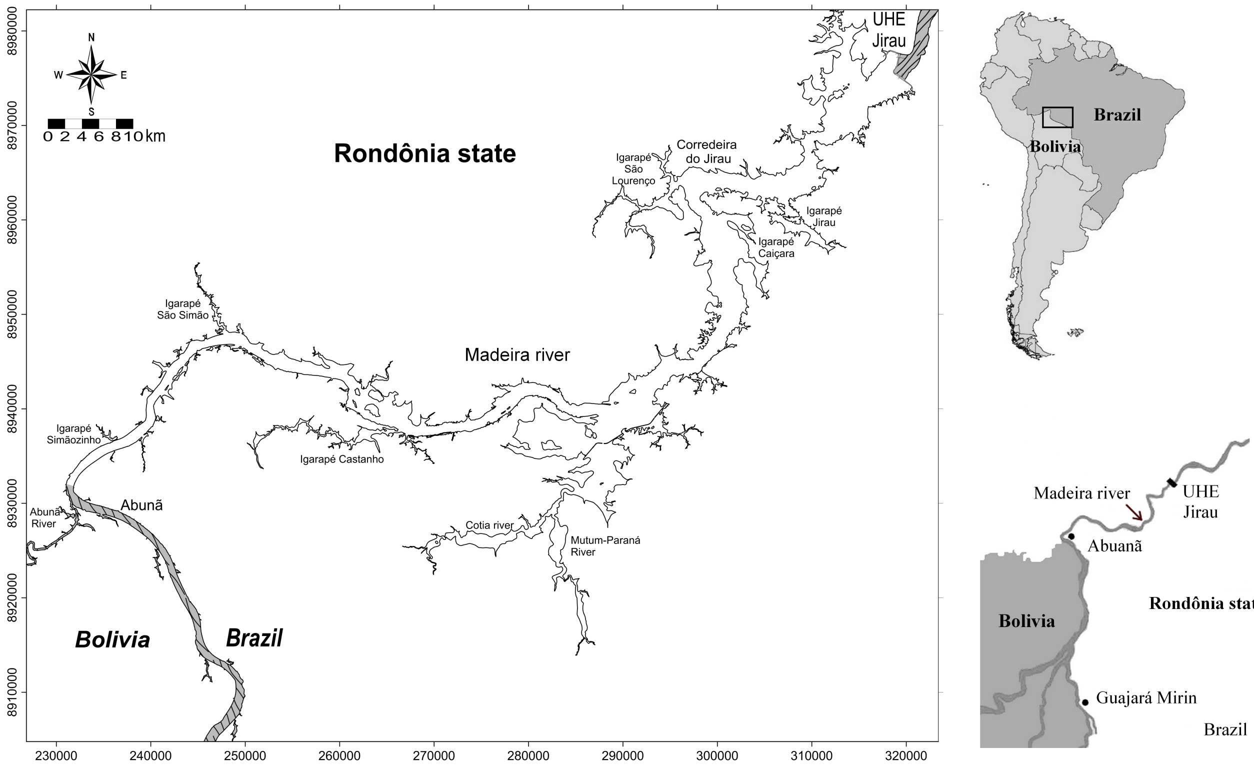

Figure 1. Location map of Jirau dam on the Madeira River, Brazil. The detail shows Jirau dam to the usual levels flood.

2. HYDRODYNAMIC AND PARTICLE TRACKING MODELS

The Madeira River waters are well mixed due to strong currents. Hence a two dimensional depth averaged model hydrodynamic (2DH) coupled with a Lagrangian model is used. The governing equations consist of a equation for the mass conservation and two horizontal momentum equations that are vertically averaged by integrating from the bottom to the surface:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial HU}{\partial x} + \frac{\partial HV}{\partial y} = 0, \tag{1}$$

$$\begin{aligned} \frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} = -g\frac{\partial \zeta}{\partial x} - \frac{gH}{2\rho_r}\frac{\partial \rho}{\partial x} + \frac{1}{H\rho_r}\Big[\frac{\partial (H\tau_{xx})}{\partial x} + \frac{\partial (H\tau_{xy})}{\partial y}\Big] \\ + \frac{1}{H}\Big(\frac{\tau_x^s - \tau_x^b}{\rho_r}\Big) + fV, \end{aligned} \tag{2}$$

$$\begin{aligned} \frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} = -g\frac{\partial \zeta}{\partial y} - \frac{gH}{2\rho_r}\frac{\partial \rho}{\partial x} + \frac{1}{H\rho_r}\Big[\frac{\partial (H\tau_{xy})}{\partial x} + \frac{\partial (H\tau_{yy})}{\partial y}\Big] \\ + \frac{1}{H}\Big(\frac{\tau_y^s - \tau_y^b}{\rho_r}\Big) - fU, \end{aligned} \tag{3}$$

where U and V are the depth integrated velocity components in the x and y directions, H is the local total depth of water, ζ is the free surface elevation, t is the time, f is the Coriolis parameter, g is the acceleration of gravity, ρ is the water density and ρ_r is the reference density, τ_{ij} represent the turbulent stresses components, parameterized by filtering techniques, cf. (Aldama, 1990; Galperim and Orszaq, 2010; Rosman, 2014), τ^s and τ^b are respectively, the magnitude of the wind stress on the water surface and the magnitude of the shear stress on the bottom.

To obtain a well-posed problem, initial conditions and appropriate boundary conditions need to be imposed along the boundary of the domain. The model also considers a wetting and drying formulation using a rough-porous layer method, more details of method is presented in Barros (2012), which allows mass conservation of system.

The Lagrangian particle-tracking model is used to identify sources, destinations, and transport pathways of particles. The hydrodynamics model velocities are used to determining the trajectory of the advected particles from this velocity field throughout time, while the diffusive component is represented by a little random displacement in the particles mass center. The two-dimensional trajectories of the simulated particles are computed by the following equation at each time step:

$$X_i^{n+1} = X_i^n + \Delta t \frac{dX_i^n}{dt} + \frac{\Delta t^2}{2!}\frac{d^2 X_i^n}{dt^2} + \mathcal{O} \tag{4}$$

where

$$\frac{dX_i^n}{dt} = U(u,v), \quad \frac{d^2 X_i^n}{dt^2} = \frac{dU}{dt} = \frac{\partial U}{\partial t} + u_i \frac{\partial U}{\partial x_i}. \tag{5}$$

Here, X_i denotes the particles coordinate, X_i^{n+1} is the new location of a particle that is advected from it previous position X_i^n by velocity components U_i obtained from the hydrodynamic model, and $\mathcal{O}$ are the despised higher order terms.

The particle transport velocity U_i follows the water body stream lines varying with time and space, according to local forcing factors. The simulate the local turbulent diffusion in the particles scattering, a random velocity deviation ϑ is introduced, which is added to the advection velocity determined by the hydrodynamic model:

$$\vartheta_i = \frac{\psi}{U_i \Delta t}\Big(D_{i,j} S_c + \frac{\Lambda_k^2}{24}\Big|\frac{\partial U}{\partial x_k}\Big|\Big), \quad D_{i,j} = 0.5\frac{d\sigma_i^2}{dt} \tag{6}$$

were ψ is a random function, Δt is the time step, $D_{i,j}$ is the turbulent diffusion, S_c represents the Schmidt number and σ is the variance, see (Rosman, 1987) for details. The hydrodynamic model defined by the shallow water Eqs.(1)-(3) are solved by finite-elements method in SisBaHiA (Base System for Environmental Hydrodynamic).

2.1 Numerical issues

The modeling hydrodynamic Eqs.(1)-(3) is approximated using a second-order finite difference scheme in time where an implicit second-order Crank-Nicholson scheme is used, cf.(Abbot and Basco, 1989), and conformal C^0 Galerkin finite element method in space (Rosman, 2014). A nonlinear version of GMRES (Saad, 1995), considering Incomplete LU factorization with Threshold (ILUT) factorization as preconditioner, with a sufficiently small tolerance, is used to solve the nonlinear system resulting from the discretization at each time step. This solver does not require storages of large matrixes, which is interesting when dealing with many degrees of freedom. The hydrodynamic model calculations are performed on a unstructured mesh in the horizontal plane but the simulated particles are free to move to any position between the mesh nodes. Therefore, the model velocities must be interpolated to the instantaneous particle positions prior to the application of the time step equations. The mesh used in this study consists of 2686 elements and 13260 nodes and is shown in Fig.2a. This was verified to be sufficient since similar solutions were obtained for more a coarser mesh. Note that this is an ongoing work and therefore a mesh convergence study will be presented in a future paper.

The bathymetry of the study area is shown in Fig.2b, were obtained by topo-hydrographic measurements in 37 sections along of the Madeira River. Isoline maps were used to complete the data set of riverbank in the tributaries of river. Wind speed and direction data were measured hourly at meteorological station located at Porto Velho City, and provided by Energia Sustentável do Brasil (ESBR), concessionaire of the Jirau project, occurred from September 2010 to October 2011. We observed in this period a standard wind speed and direction of about 3 ms^{-1} and 210°, respectively.

The reservoir's water level varies according to the inflow hydrograms, according to the rules of operation of the da UHE Jirau where will be operated with a variable upper reservoir level, minimum and maximum normal water level will be 82.5 m and 90 m.

The initial conditions were horizontal level and velocity in all mesh nodes. At all water-land boundary nodes, the null tangential velocity component is imposed. According to Eq.(3), the bottom friction coefficient is written in terms of the Chezy coefficient, which depends on the amplitude of the equivalent bottom roughness, ε. Therefore, the amplitude of the equivalent bottom roughness, was defined on the basis of the characterization and distribution of bottom sediment. In the Madeira River and main tributaries, observed that sand is predominant in the region, $\varepsilon = 0.030$ m. The values of 1000 kgm^{-3}, 1.230 kgm^{-3} and 9.781 ms^{-2} were assumed for the density of water and air, and gravitational acceleration. The hydrodynamic model simulated a period of 1-year and computational time step of 120 s was considered.

In this work, the mesh and time step used for the hydrodynamic model were the same considered for the Lagrangian simulation. The Lagrangian particle tracking model is used to study the dispersion of particles, representing the advection of fish eggs and larvae. The particles are released in the main spawning region for Jirau Dam and in the area where fish eggs an larvae are plentiful during this period.

The data of fish eggs and larvae were obtained from a specialized aquaculture company to carry out field surveys to obtain precise information on the early stage and evolution on fish eggs and larvae. Therefore, in the present study, for the simulation of fish eggs and larvae transport was considered an average density of eggs and larvae of the collected

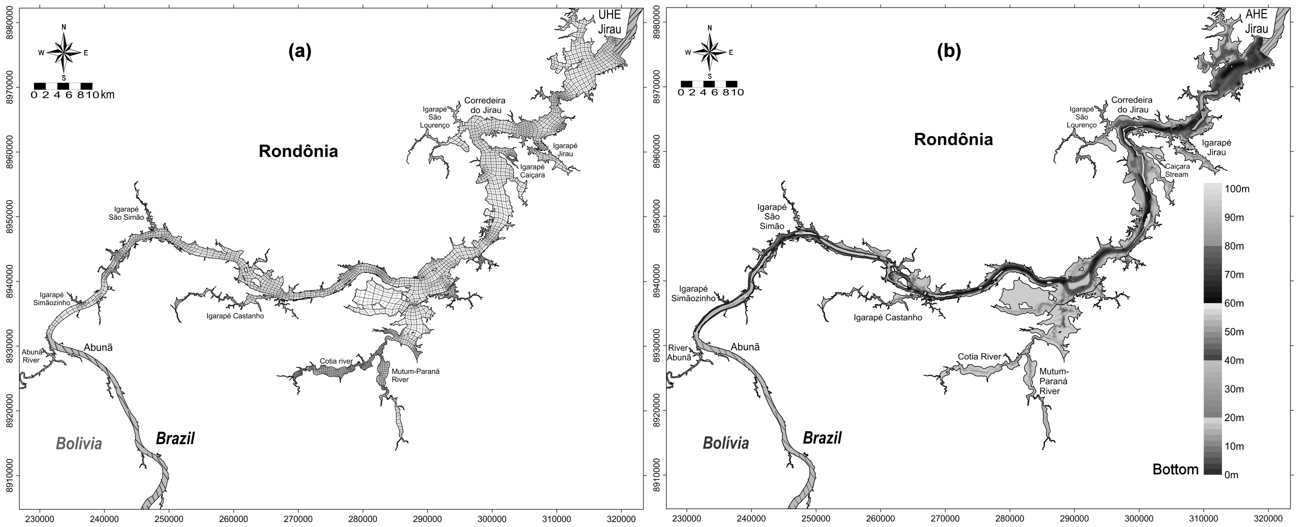

Figure 2. (a) Show the unstructured mesh of discrete domain model made up of 2686 biquadratic quadrilateral elements and 13260 nodes, and (b) show the bathymetric features of study area.

species varying between 1.003 to 1.030 g ml^{-1} compared with water density of unit volume which is 1.0, and diameters of between 0.2 and 2 mm used to simulate the fish eggs and larvae migration. Furthermore, the following assumption were imposed:

- The fish eggs are simulated as neutrally buoyant passive particle, and the fish larvae were transported with the flow without settling.
- Based on planktonic larval duration of the tropical fish species. The larvae complete their plancktonic larval duration in approximately 10 days, and the released eggs form larvae is in a day in tropical conditions as their hatching time is reported to be less than a day.
- The larval abundance in a region is affected by predation, mortality and behaviour. In this study, these aspect were neglected as the variation in these parameters in the study domain is not know, and it is difficult to interpolate the same in spatial scale in the numerical model.
- Active fish larvae tend to migrate vertically, but due to the strong current of Madeira River to carry forward the larvae. Thus, is assumed that the change in distribution of larvae due to vertical migration is negligible.

3. RESULTS AND DISCUSSION

3.1 Hydrodynamics and fish eggs drift

Velocity fields behavior along of study domain are shows in Fig.3 for the months of November, February, June, and September which corresponds to periods of high and low waters of the Madeira River. Although all the selected events represent the time when wind is blowing from the west-southwest (WSW), results of the simulations illustrate the hydrodynamic conditions.

For the month of November the maximum value of the velocity is of the order of 1,2 m s^{-1}, as see in Fig.3a. It is corresponds to the beginning of the high water period. This behavior is consistent with low intensities of current in this period. In the month of the February, which corresponds to the period of high water levels, we observed maximal current values around of 3.5 ms^{-1}, Fig.3b. The maximal current values is around of 2.0 ms^{-1} and minimum of about 1.0 ms^{-1}, see Fig.3c. The low speed which corresponds to September, with values lower of 1,0 m s^{-1}, is shown in the Fig.3d. This results are in accordance with the data observed in locus.

Results for the drift of fish eggs and larvae released during all lagrangian simulations, are shows in Fig.4. It is interesting to note that fish eggs and larvae are transported landward from their initial position to central axis of the reservoir. Fig.4 shows the time evolution of the of fish eggs and larvae particles trajectories released for each event studied. Fig.4a shows that fish eggs and larvae were advected to downstream of dam during the first 72 hours of track in the reservoir. The figures were formed by accumulating of the percentages of the 24 hours periods. We observe that over 70% of eggs and larvae in study area has less than 120 hours, or 5 days. In the month of February, Fig.4b, most of the eggs and larvae were advected to downstream of the dam have a shorter period of path shorter than 48 hours in reservoir. We observe than the most of fish eggs and larvae are advected downstream in reservoir and are less than 36 hours drifting.

If we accumulate the percentages of each 24-hour interval, we verified that around 80% of eggs and larvae present in the reservoir has less than 5 days or 120 hours. In June, Fig. 4c, we observe that the majority of eggs and larvae with paths time smaller than 24 hours are advected downstream of the dam. We observe that about 82% of fish eggs and larvae in reservoir are less than 120 hours. In September, Fig.4d, the simulation show that the majority of eggs and larvae with paths time smaller than 144 hours, or 6 days and are advected downstream the dam. We observe that even in the month of September, when the flow rates are lower, the travel time of majority of eggs and larvae is inferior to 6 days.

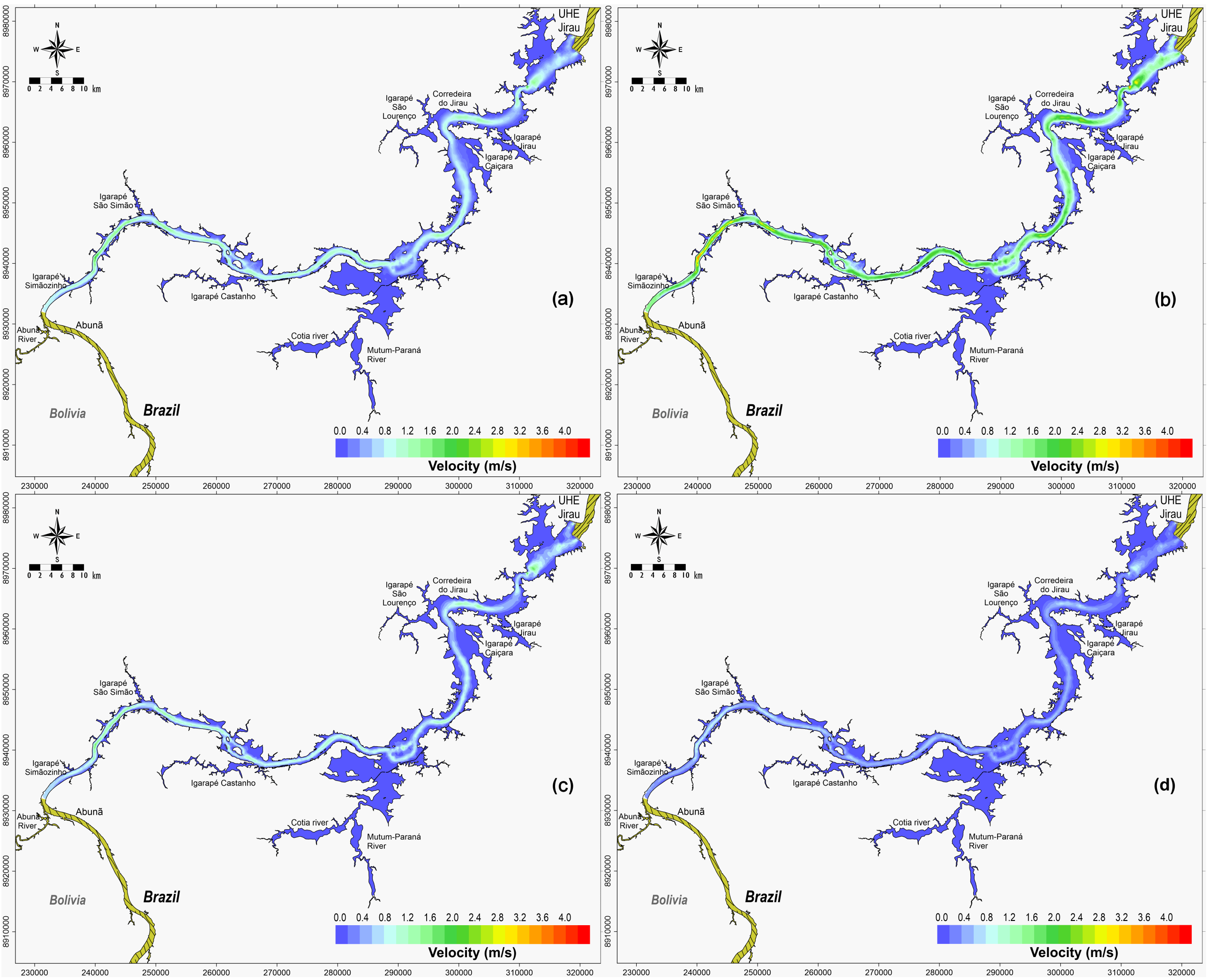

Figure 3. Horizontal fields of the velocity in the Jirau Dam for the months of: (a) November, (b) February, (c) June and (d) September of hydrodynamic simulations.

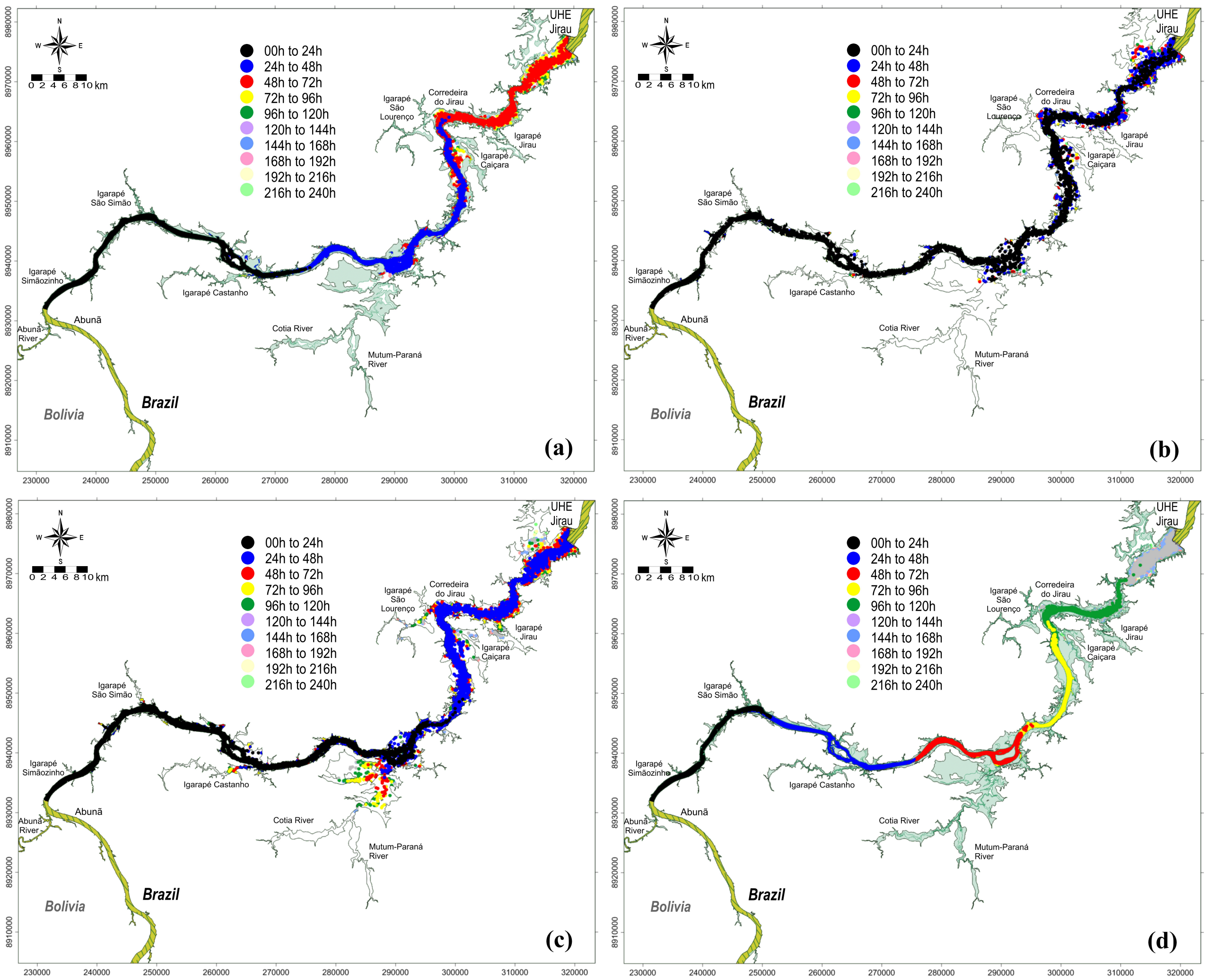

Figure 4. Simulation of fish eggs and larvae dispersal in the months: (a) November, (b) February, (c) June, (d) September at Jirau dam.

4. Conclusion

This paper addressed the issue of the drift processes of fish eggs in the backwater of the Jirau Dam. Despite the construction of the reservoir in Madeira river, the results indicate a regime of flow that is typically fluvial and maintain the similar hydrodynamic characteristics of Madeira river. The amount of eggs and larvae with more than 9 days of drifting in reservoir is spread on, the dendrites, embayments of the domain studies. We observed that the low percentages of loss due to retentions in wetlands can be considered irrelevant. Thus, this study show that particle transport modeling can be an effective tool and decision support system to identifying the locations of potential retention areas for fish eggs.

5. ACKNOWLEDGEMENTS

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